Aplications of dust research in solar energy technologies

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Outline

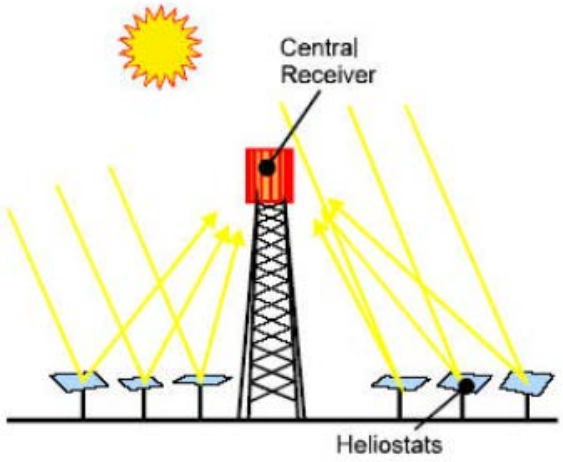
- Solar technologies
- Effects of dust on solar plants
  - Soiling
  - Degradation & abrasion
  - Attenuation of radiation
  - Circumsolar radiation

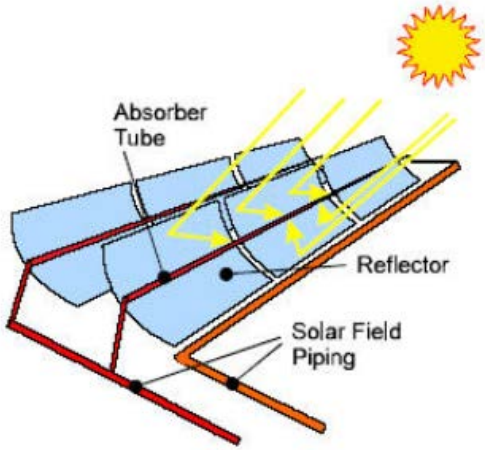
Photovoltaics

- Semiconductor material generates electricity
- Incoming light from hemisphere above surface utilized
- Storage using batteries

Image: Greenwish Partners Inc.

Concentrating Solar Power (CSP)

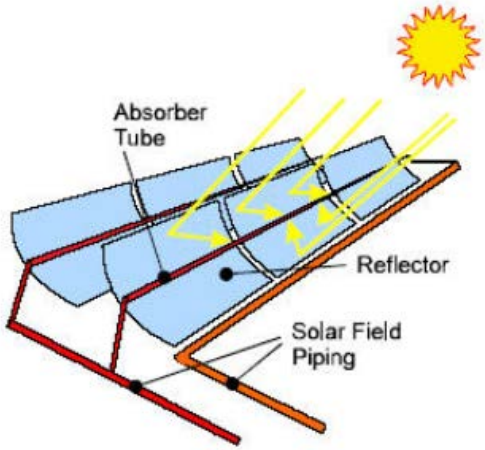




Images property of: Torresol energy, MASEN, SolarPACES

Concentrating Solar Power (CSP)

- Concentration of direct sunlight with mirrors to achieve high temperatures
- Provision of electricity (turbine cycle), process heat, desalination
- CSP uses only direct component of solar irradiation
- Cost effective thermal storage option



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Effects of dust on solar plants

- Soiling of solar collectors
- Degradation and abrasion of solar collectors
- Attenuation of radiation
- Circumsolar radiation

Soiling

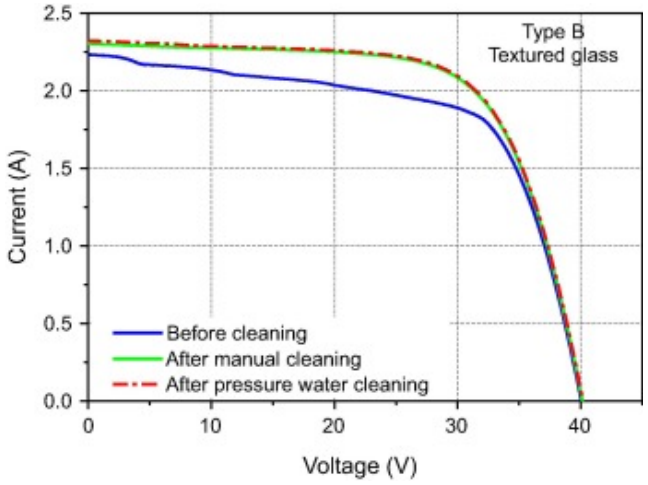
- Microscopic particles such as mineral dust, pollen & anthropogenic pollutants accumulate over time on optical solar materials
- Effect: Efficiency reduction
- Action: Cleaning effort and costs vs loss of revenues;
- Relevant in operation, yield analysis and site selection, local water distribution

Image: Abengoa Solar

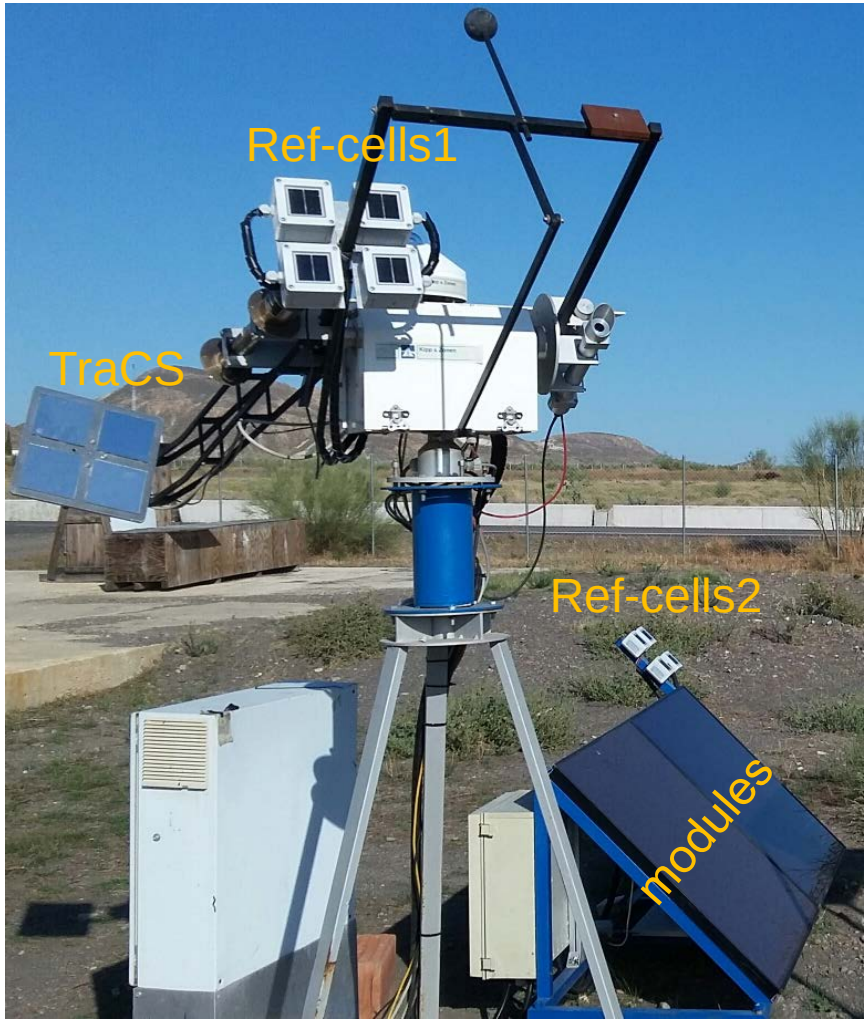
Measurement of soiling

PV

- Short circuit current or IV-curve of sample cells / modules
- Cleanliness = $I_{SC,soiled}$ / $I_{SC, clean}$
- Measurement:
  - Reference cell I_{SC}
  - Modules with IV-curve-tracer



J. Lopez-Garcia, A. Pozza, T. Sample, Long-term soiling of silicon PV modules in a moderate subtropical climate, Solar Energy, 2016

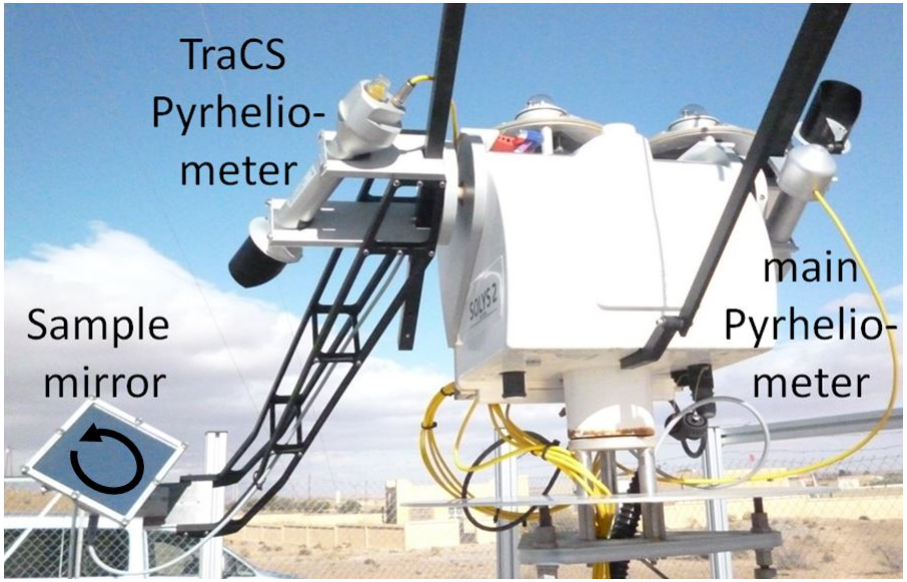


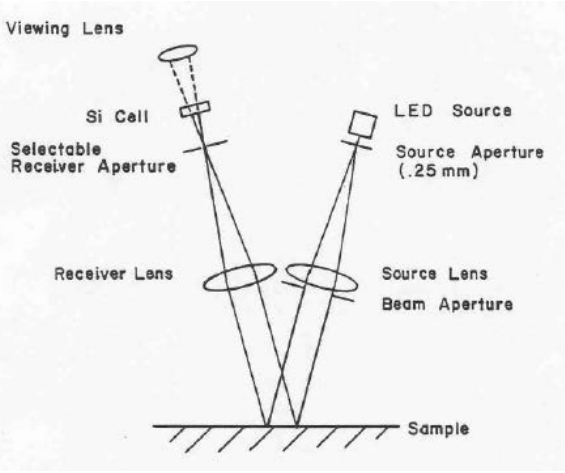
DLR measurement setup at PSA

Measurement of soiling

CSP

- Solar weighted specular reflectance ρ
- Cleanliness = ρ_{soiled} / ρ_{clean}
- Measurement:
  - TraCS
  - Handheld devices



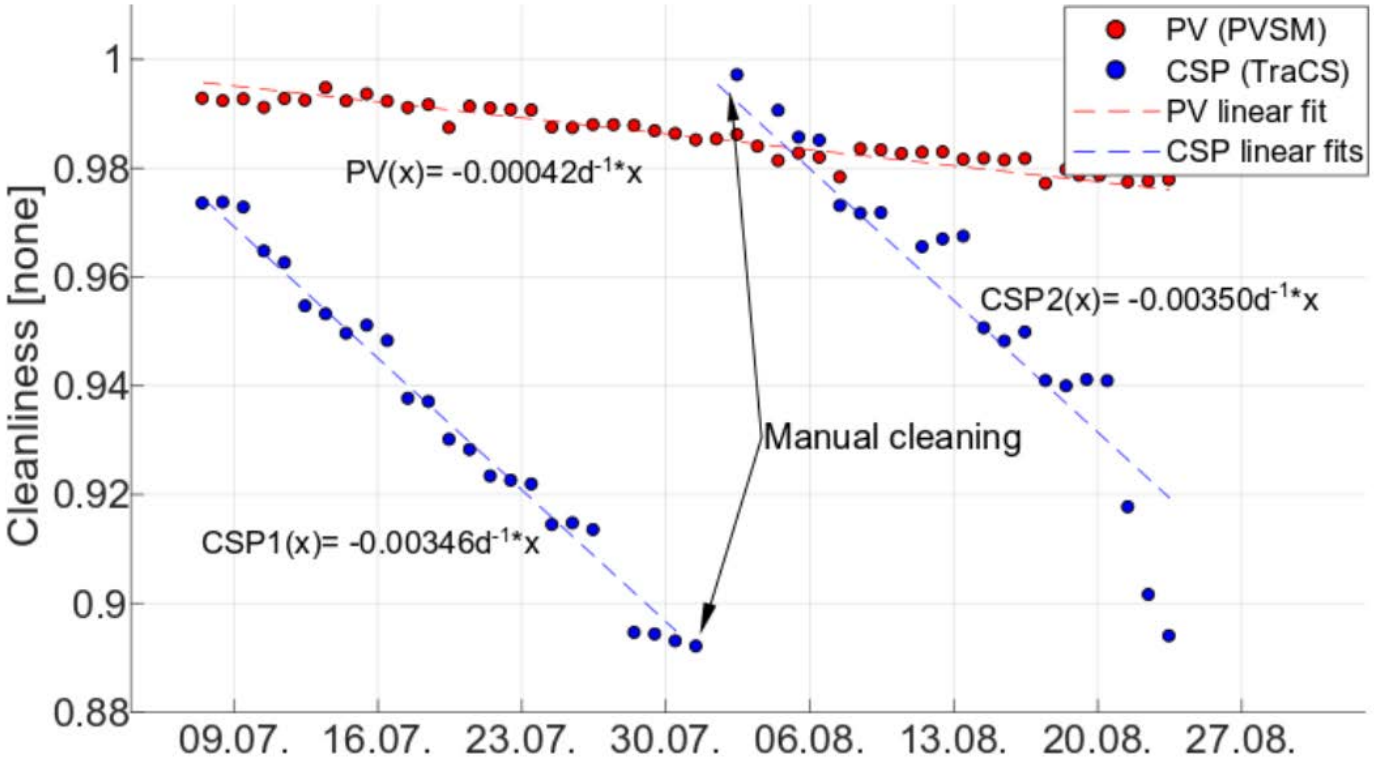


Wolfertstetter, F., Pottler, K., Alami, A., Mezrhab, A., & Pitz-Paal, R. (2012). A novel method for automatic real-time monitoring of mirror soiling rates. SolarPACES 2012.

A. Fernández-García, F. Sutter, L. Martínez-Arcos, C. Sansom, F. Wolfertstetter, C. Delord, Equipment and methods for measuring reflectance of concentrating solar reflector materials, Solar Energy Materials and Solar Cells, Volume 167, 2017

Soiling

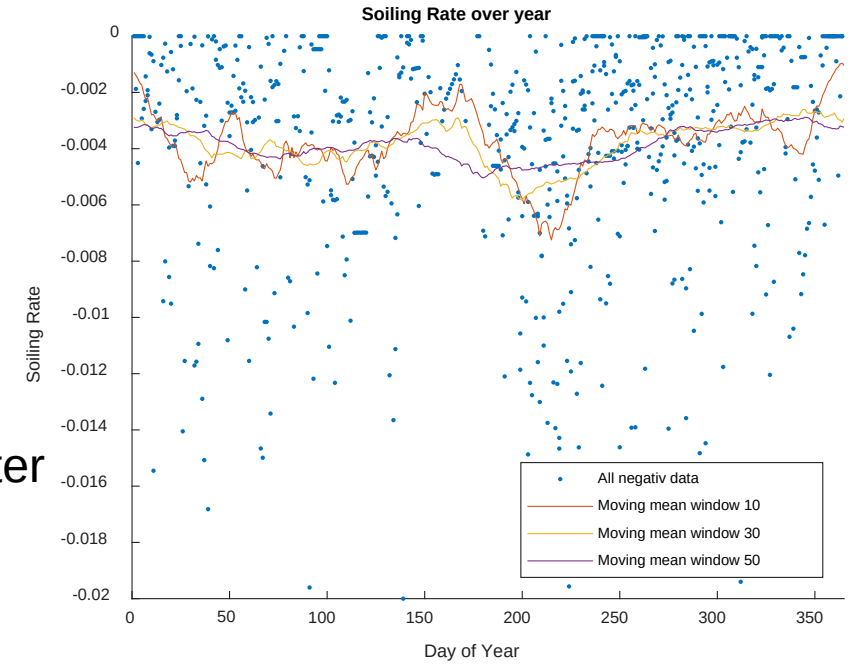
- CSP is affected by soiling 8-9 times more than PV

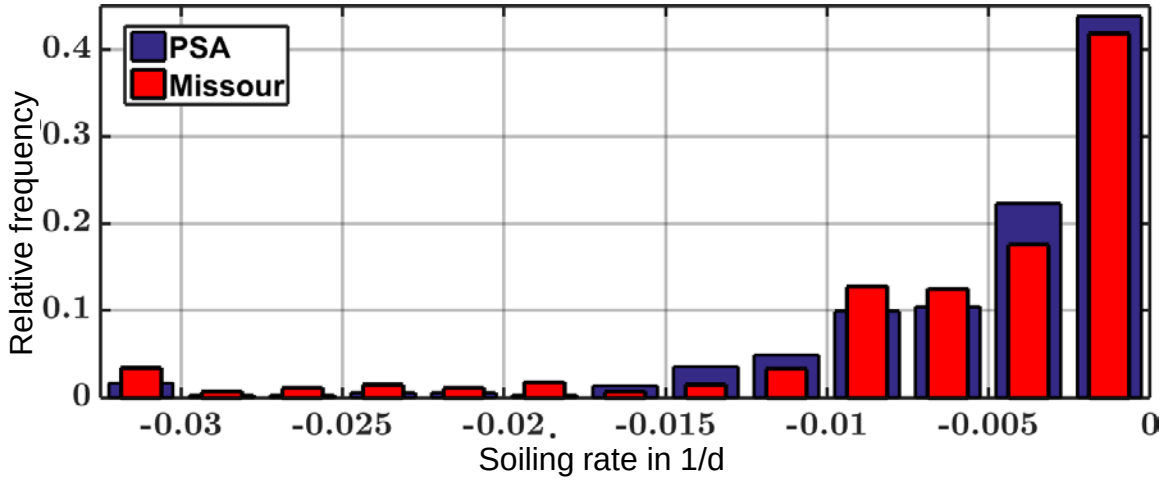


P. Bellmann, Investigation of soiling on mirror and glass samples with regard to power losses in CSP and PV technologies. Diploma thesis, Technische Universität Dresden, 2017.

Soiling rate

- Soiling rate = reduction of cleanliness over time
- Soiling rate is dependent on time and location
- Not (yet) a standard measurement parameter
- Little information available in target regions for solar projects

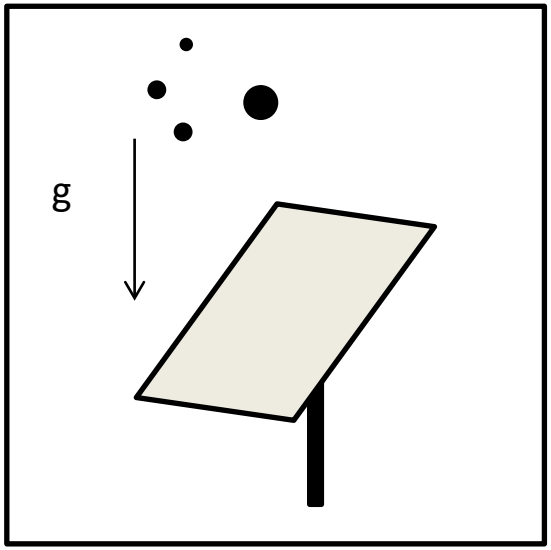




Soiling model

Aim: predict soiling rate on solar mirrors from other weather data.
Test and validate with measurement data

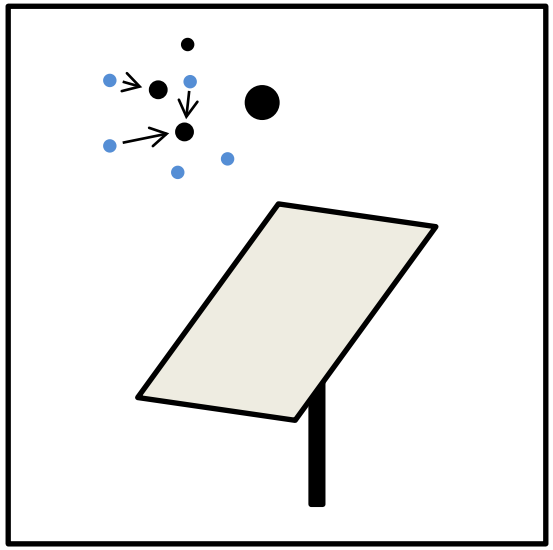
Sedimentation



- Gravitation

$$v_{S,p} = \frac{g\ {d_p}^2(\rho_{Aerosol} - \rho_{Luft})}{18\ \eta_{Luft}}$$

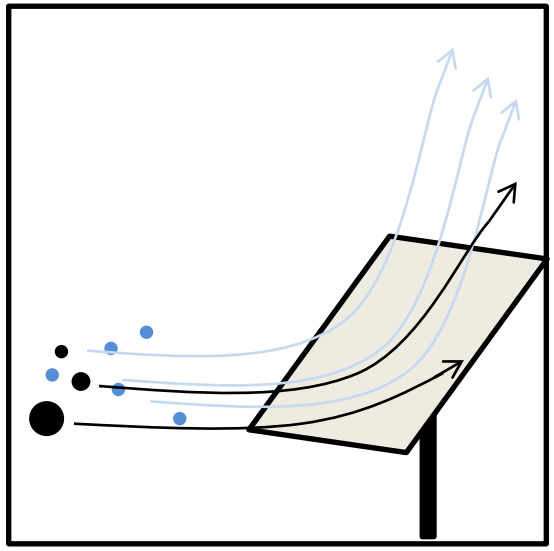
Brownian motion



- Thermal motion

$$v_B = a_{Brown}\ u_{Wind} \left(\frac{\nu_{Luft}}{D_B}\right)^{-\gamma}$$

Impaction



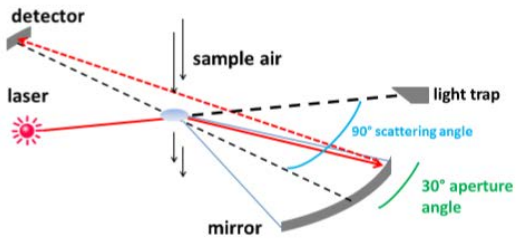
- Air stream/wind

$$v_{Im} = a_{Im} \cdot \frac{\sigma_{Ausrichtung}\ u_{Wind}}{1 + \exp(-f_{Im} \cdot (St - 1))}$$

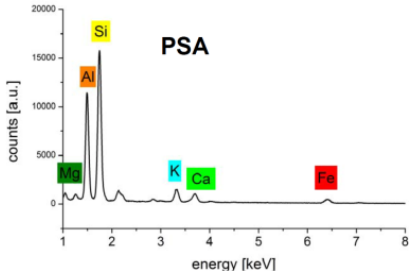
Also considered:
Rebound, resuspension, rain washing, cementation, mirror/panel orientation

Soiling model: input data

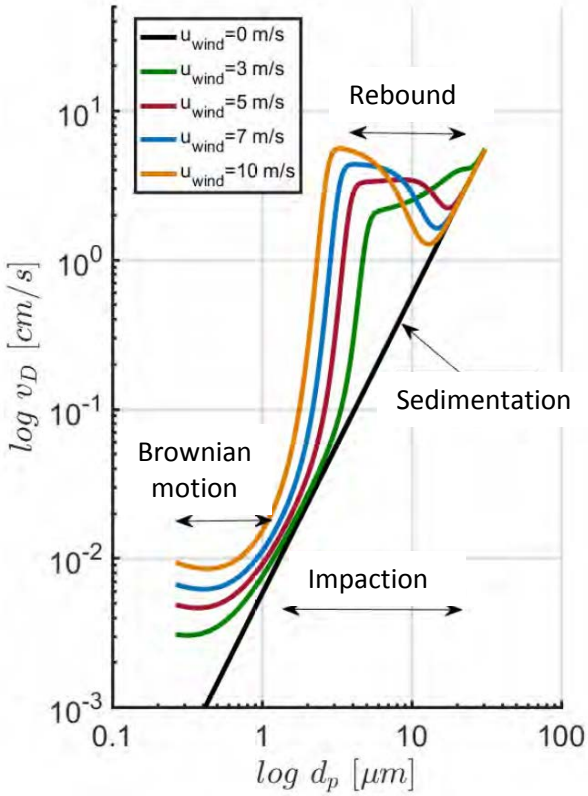
- Model is trained with a long term measurement dataset from PSA containing:
  - Aerosol particle number concentration from 0.25 µm - 30 µm
  - Wind, relative Humidity, rain, irradiance, dew, temperature, atmospheric pressure, etc.



Optical particle counter



Soil properties



Visibility

Flysand

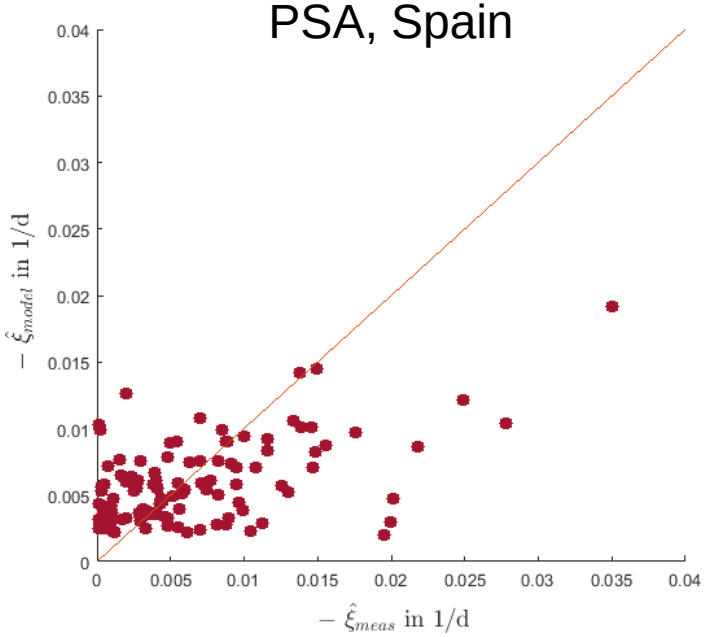
3D Wind, rain, temperature

Soiling model performance

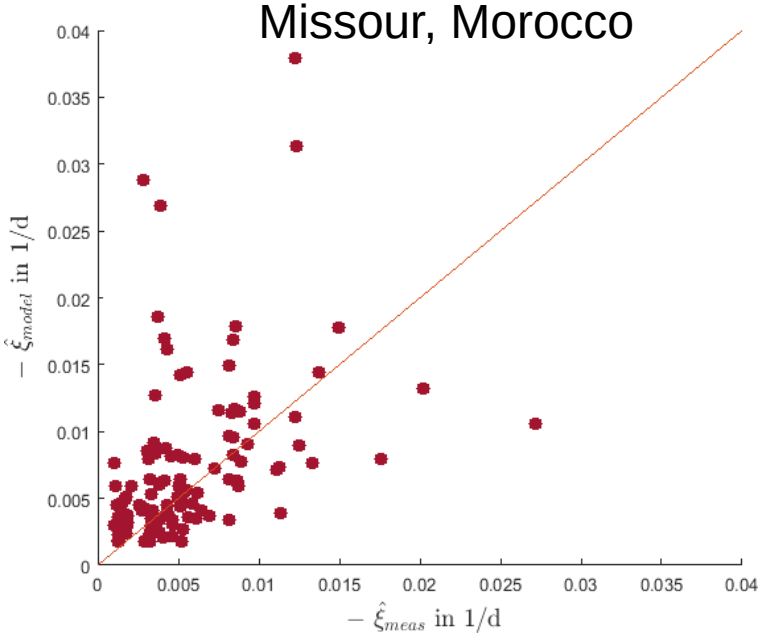
- Model validated for two sites
- RMSE = 2 x soiling rate measurement accuracy
- Bias = 0.5 x soiling rate meaurement accuracy

	Bias (· $\%/d$)	RMSE ($\%/d$)
PSA Training Set	0.08	0.43
PSA Test Set	0.11	0.44
Missour	0.09	0.46

PSA, Spain



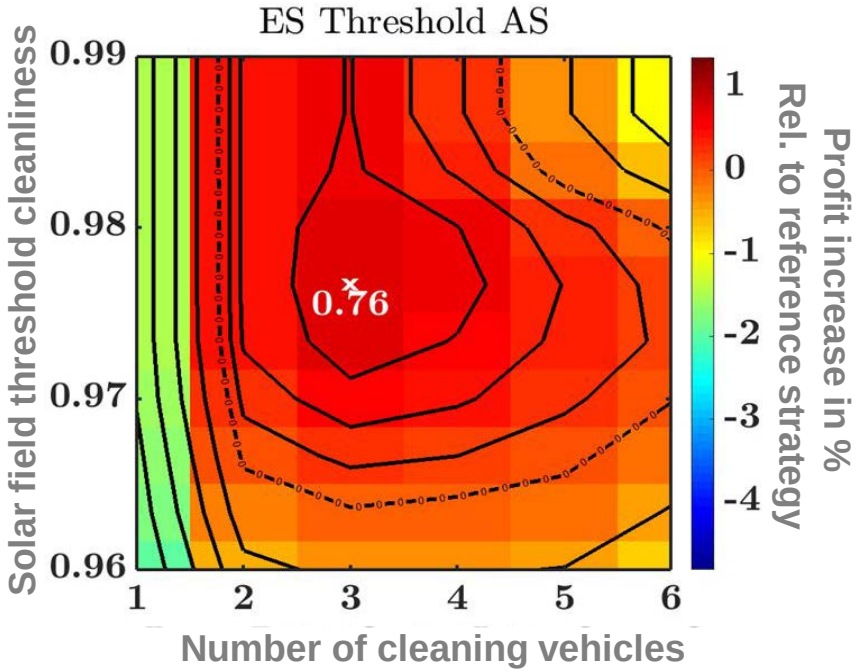
Missour, Morocco



Soiling and condensation model applied to CSP solar field – DLR Report, WASCOP H2020 project D3.2, 2018, to be published online on www.wascop.eu,

Soiling model and cleaning optimization

- Trade-off between **cleaning cost** minimization and **revenue** maximization
- **Time resolved soiling rate** information improves cleaning scheduling
- Adaptation of cleaning intensity on cleanliness **increases profit** significantly
- **Soiling forecast** could further increase profit during operation: planned within recently started SOLWATT H2020 project in collaboration with BSC



Wolfertstetter F, Wilbert S, Dersch J, Dieckmann S, Pitz-Paal R, Ghennioui A. Integration of Soiling-Rate Measurements and Cleaning Strategies in Yield Analysis of Parabolic Trough Plants. ASME. J. Sol. Energy Eng. 2018

Wolfertstetter, Fabian (2016) Auswirkungen von Verschmutzung auf konzentrierende solarthermische Kraftwerke. Dissertation, RWTH Aachen.

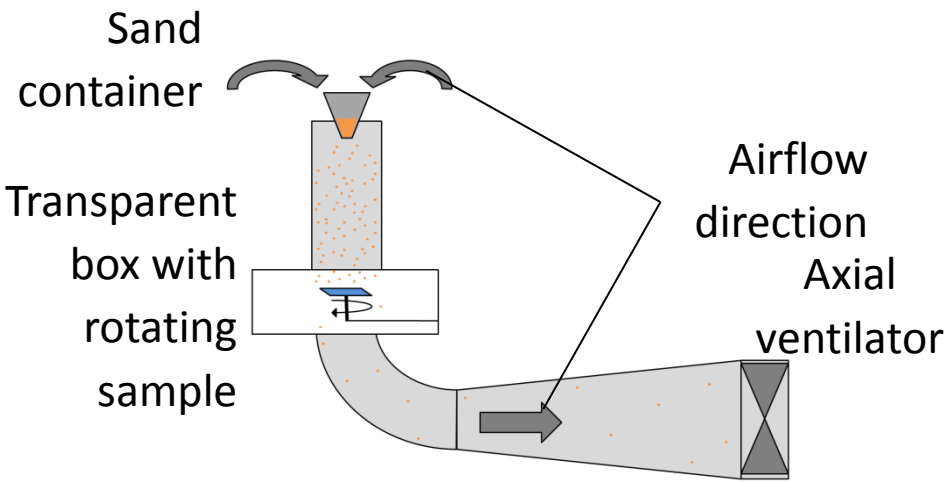
Effects of dust on solar plants

- Soiling of solar collectors
- Degradation and abrasion of solar collectors
- Attenuation of radiation
- Circumsolar radiation

Abrasion due to dust storms

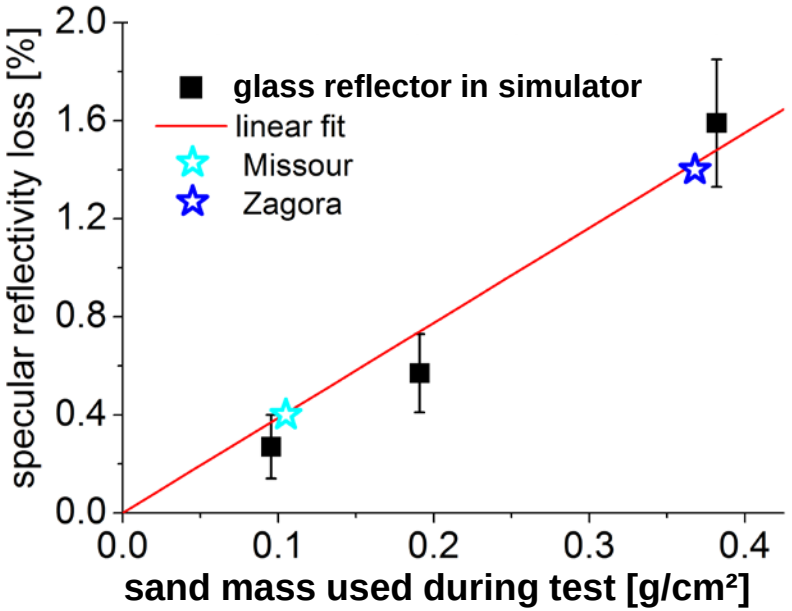
- Permanent damage to optical surfaces
- Analysis of meteorological data (wind, humidity, etc.) and flying sand concentration measurements at desert sites, co-located with mirror/PV exposure
- Objectives:
  - Determine degradation rate at different sites
  - Determine test parameters for realistic accelerated ageing tests in dust storm simulation chambers

BSNE sand trap; Mirror exposure rack



Determination of dust storm chamber test parameters

- Particle counter measurements from Missour and Zagora
  - Grimm: optical, 1min resolution, 31 size channels (both sites)
  - HVS: gravimetric (ASTM D4096-91) (>10h resolution) (Zagora)
- Reflectivity loss from mirror samples measured
- Impacting particle mass related to reflectivity loss found in the field
  - Reproduction in dust storm chamber



Wiesinger, F., Sutter, F., Wolfertstetter, F., Hanrieder, N., Fernández-García, A., Pitz-Paal, R., & Schmucker, M. (2018). Assessment of the erosion risk of sandstorms on solar energy technology at two sites in Morocco. Solar Energy, 162, 217-228.

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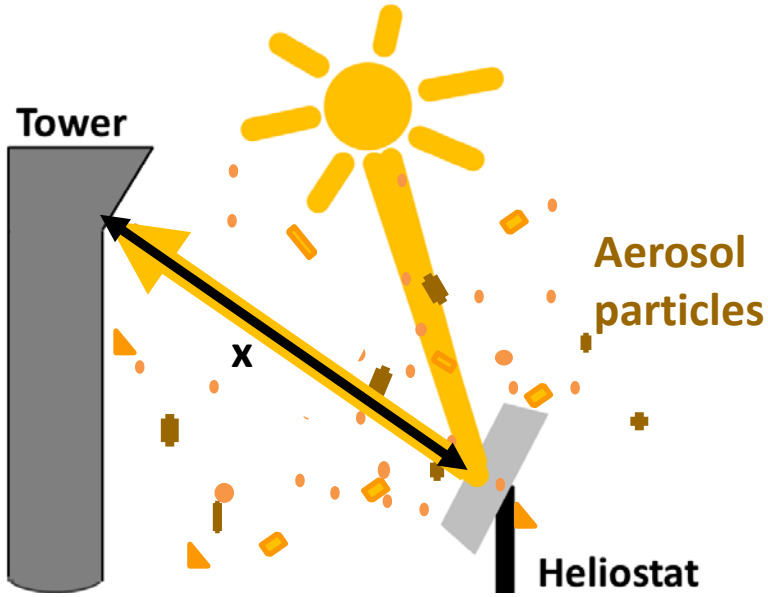
Attenuation of radiation



- Solar radiation is lost due to aerosol extinction
  - on the way to the solar collectors
  - on the way from the heliostats to the receiver
- Atmospheric extinction of solar radiation between heliostat and receiver in solar tower plants can vary strongly with site and time
- Important parameter: transmittance dependent on slant range x →

$$T_x = \frac{DNI_{rec}}{DNI_{helio}} = e^{-\beta_{ext} \cdot x}$$

extinction coefficient

Lambert-Beer-Bouguer law

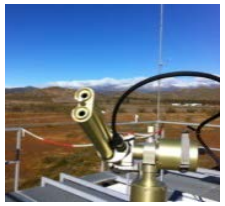
- This effect reduces the plant yield and cannot be neglected

Beam attenuation in CSP tower plants

Extinction of Solar Radiation

- Different methods to determine the atmospheric extinction:
  - Usage of commercially available instruments like e.g. scatterometer
  - Development of transmittance model based on DNI measurements

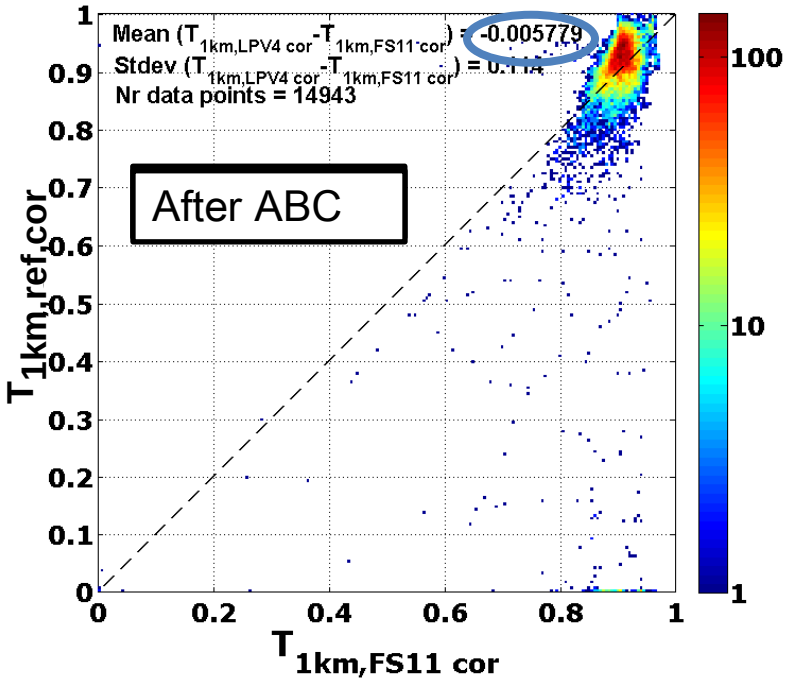
FS11scatterometer



libRadtran

Absorption & Broadband Correction (ABC)

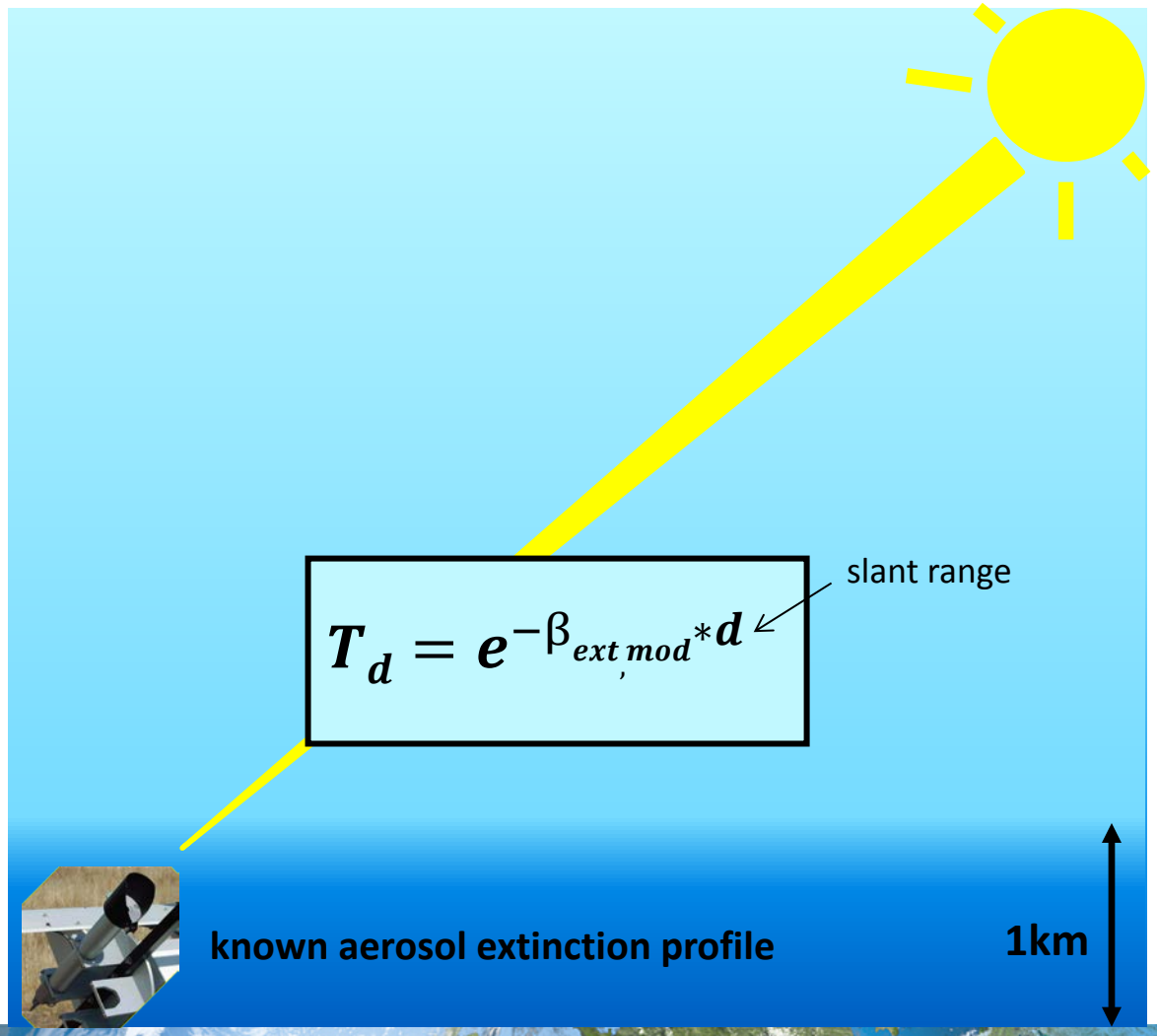
ABC required to obtain correct broadband transmittance



Transmittance model based on DNI measurements

Compare clear sky DNI measurement
To clear sky DNI for one fixed atmosphere without aerosol
→ Estimate of AOD
Assume that aerosol height profile is known
→ Determine extinction coefficient close to ground

→ Validation satisfying for three sites in Spain & Morocco (T_{1km} ~ 0.85)
→ Bias of -0.02 to 0.013 assuming constant profile in the 1st km over ground



Sengupta, M., Wagner, M., 2011: "Impact of aerosols on atmospheric attenuation loss in central receiver systems". SolarPACES conference, Granada, Spain.

Hanrieder N., M. Sengupta, Y. Xie, S. Wilbert and R. Pitz-Paal (2016), "Modelling Beam Attenuation in Solar Tower Plants Using Common DNI Measurements." In: Solar Energy 129, 244-255.

Effects of dust on solar plants

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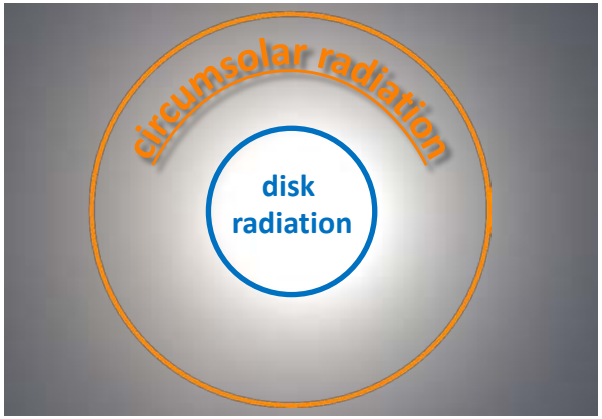
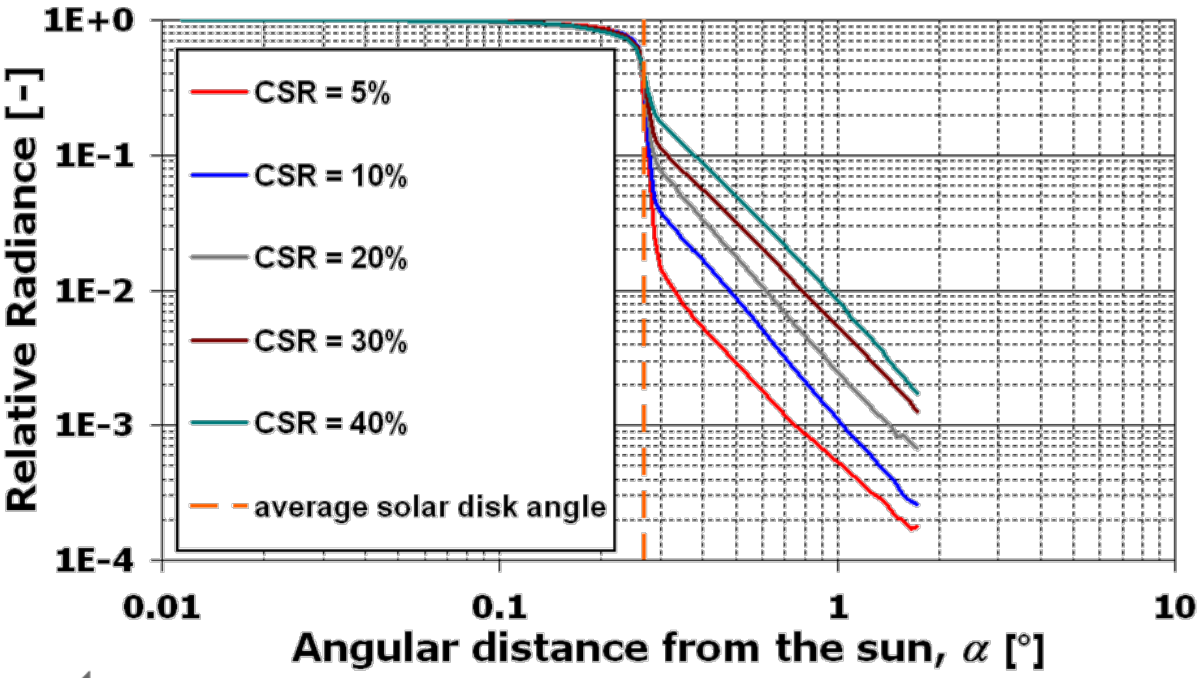
Circumsolar Radiation

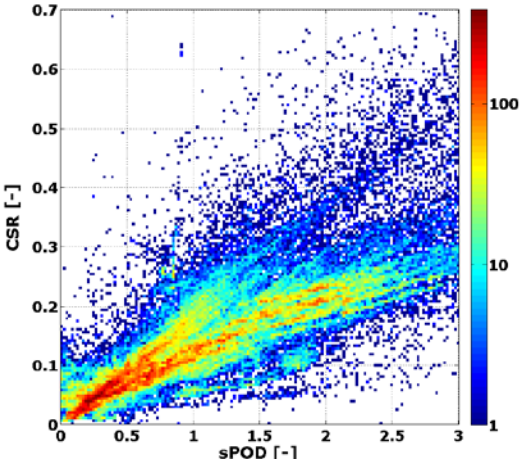


- Circumsolar radiation is forward scattered solar radiation
- **Concentrating collectors use:**
  nearly the complete disk radiation
  +
  a smaller fraction of the circumsolar radiation

Circumsolar radiation – measurement and modelling

- Circumsolar radiation described by **sunshape** & the circumsolar contribution to DNI
- **Measurement options**
  - SFERA system: SAM (Sun & Aureole Measurement), sun photometer + software
    - Results: sunshapes, circumsolar contribution to DNI
    - additional determination of aerosol & cloud properties
  - 2 pyrheliometers with different apertures
  - RSI based measurement
- **Models** based on aerosol and cloud information





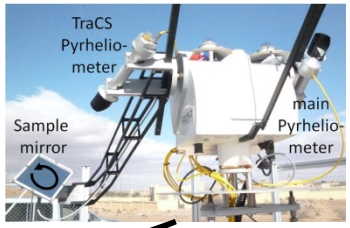
enerMENA network

Operational since 2010 -2013

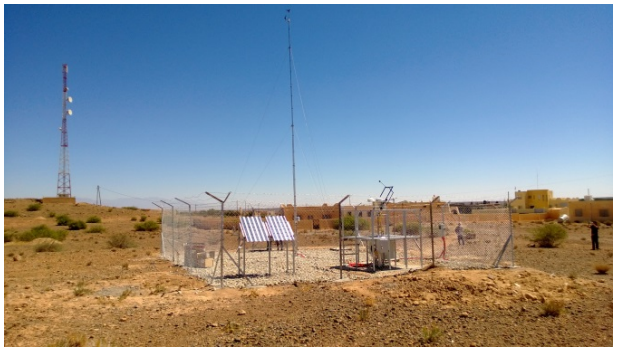
12 meteorological measurement stations (solar irradiance, temperature, pressure, relative humidity, wind, etc…)

Scatterometer FS11from Vaisala

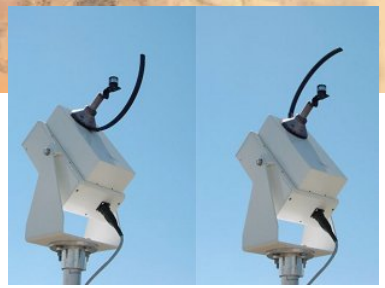
Grimm EDM164 Particle counter



TraCS for mirrror soiling



HVS-TSP16 from MCZ: gravimetric measurement principle



Schüler, David, et al. "The enerMENA meteorological network–Solar radiation measurements in the MENA region." AIP Conference Proceedings. Vol. 1734. No. 1. AIP Publishing, 2016.

Aplications of Dust Research in Solar Energy Technologies

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- Effects of dust on solar plants
  - Soiling
  - Degradation & abrasion
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  - Circumsolar radiation

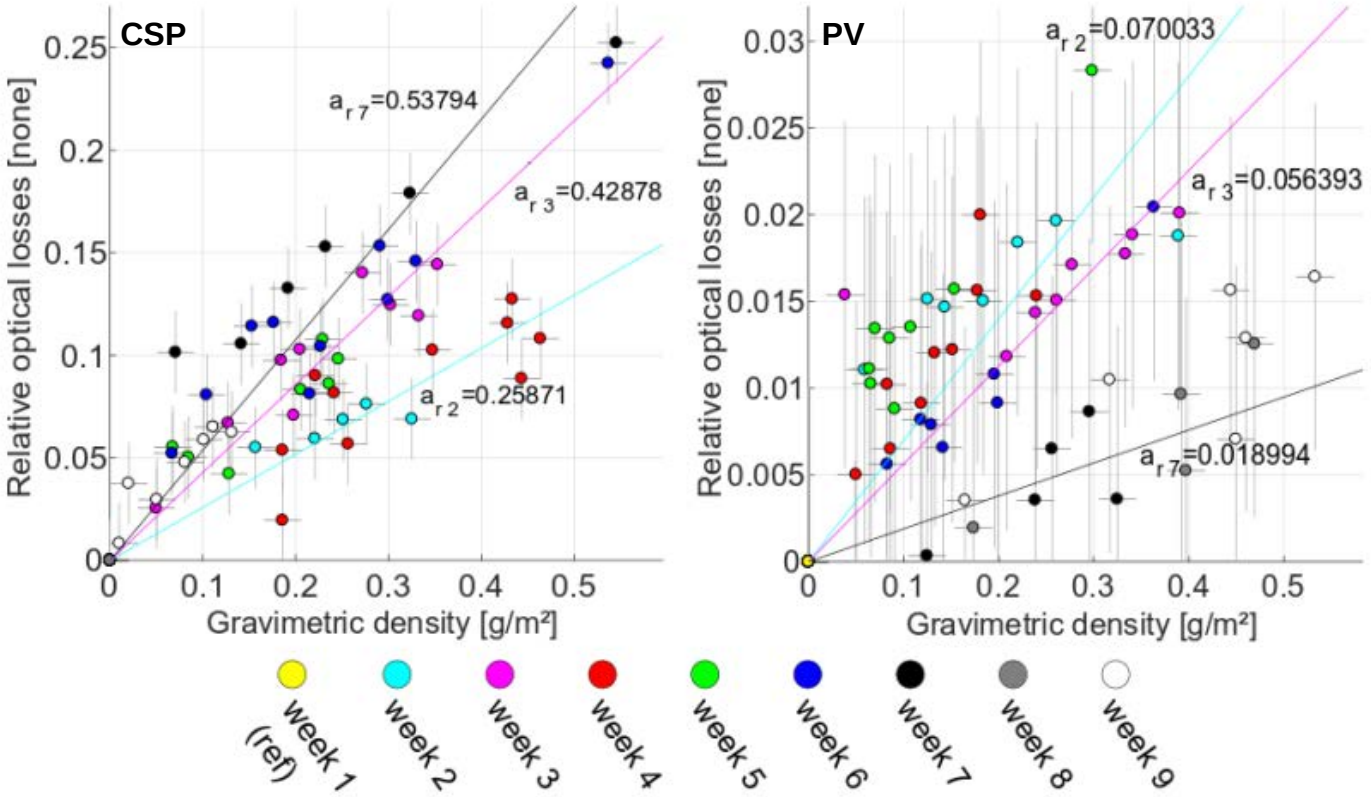
http://www.dlr.de/sf/en/desktopdefault.aspx/tabid-10224/17488_read-44933/

Aerosol related measurements at PSA

- Ceilometer
- CIMEL Sun Photometer
- Spectral irradiance in minute time resolution
- Tiltable Raymetrics LIDAR

Composition makes a difference

- Different sampling periods show different mass/optical loss ratios due to different particle size distribution and composition



Soiling forecast

- The soiling model will be integrated to BSC‘s MONARCH atmospheric dust transport model for an operational forecast
- A soiling map can be created from reanalysis with integrated model

Within recently started SOLWATT H2020 project